A STUDY OF INTERLAMINAR FRACTURE IN UNIDIRECTIONAL COMPOSITE MATERIALS

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ABSTRACT

Using the standard compact tension specimen (Fig.1), Parhizgar et al [1,2] have studied the interlaminar fracture behaviour of unidirectional glass/epoxy composite laminates. A rigorous fracture analysis of these tests was the objective of this investigation. In this paper, a short summary of the fracture analysis followed by a discussion of the results obtained is given.

SUMMARY OF FRACTURE ANALYSIS

Using the standard compact tension specimen shown in Fig.1, Parhizgar et al [1,2] have studied the interlaminar fracture behaviour of unidirectional, glass/epoxy composite (SCOTCH-PLY 1002) material. In that study, tests were carried out by varying the fiber orientation angle α (Fig.1) with respect to the plane of the initial crack. The open circles in Fig.2 are the measured critical loads P_C at the onset of crack propagation for $\alpha = 0^\circ, 30^\circ, 45^\circ$ 60° and 90°. Since fracture in these tests takes place under varying degrees of interaction between the opening (mode I) and in-plane sliding (Mode II) modes the data is well suited for a critical evaluation of the predictability of linear elastic fracture mechanics approaches.

The energy release rate denoted by G provides a more useful parameter in the phenomenological study of interlaminar fracture in composites. It is mathematically well defined and physically measurable in experiments. Therefore, accurate calculation of the energy release rate associated with assumed crack extension behaviour is an integral part of the fracture analysis. Finite element analysis happens to be an ideal tool for this purpose.

TRIPLT is the acronym for a shear-flexible triangular laminated composite plate finite element and the associated structural analysis program that was used in the present study. The research and rationale leading to the development and evaluation of TRIPLT is well documented in Ref [3] and hence only its salient features are summarised here. The triangular element illustrated in Fig.3 has three nodal points located at its vertices and fifteen degrees of freedom are associated with each node. The mathematical formulation takes into account anisotropic elastic behaviour of constituent plies, bending-stretching coupling, and transverse shear deformation effects. Complete cubic polynomials are used to approximate the three displacement components (u,v,w) and the two rotations (θ_x, θ_y) within the element. The displacements and rotations along with their first derivatives are chosen as the nodal parameters, enabling direct evaluation of stress resultants at the nodes. The versatility of TRIPLT in providing accurate numerical solutions to some problems in mechanics of composites has been demonstrated [4,5]. In this study, exploiting the pure stretching behaviour of the compact tension test specimen, all the bending degrees of freedom were suppressed in the analysis.

From an elastic energy balance consideration, Irwin[6] showed that the strain energy released during an incremental crack extension in a coplanar fashion is equal to the work done in closing the crack to its original length. This statement in equation form is the well known crack closure integral. A novel finite element technique to evaluate the mode I(G_I) and mode II (G_{II}) components of the energy release rate G, based on computing the crack closure integral has been proposed by Rybicki and Kanninen[7]. The accuracy (for a given mesh) and computational efficiency (for acceptable accuracy) of this technique can be considerably improved by employing a higherorder finite element model such as TRIPLT instead of constant strain elements as advocated by Rybicki and Kanninen. The significant advantages of the new method of analysis [5] are: (1) It avoids dealing with the details of singular stress distribution around the crack tip where there are the added complexities of material anisotropy and mode interaction; (2). It permits separation of G into its components G_I and G_{II} in a mixed mode problem; (3) It assures high accuracy even with a coarse mesh; (4) The finite element modelling does not require special crack tip elements; and (5) The crack closure integral is evaluated directly from nodal forces and nodal displacements and hence stress calculations are unnecessary. This technique was used in the present study to calculate $G = G_I + G_{II}$ as a function of α for the compat tension specimen.

The energy release rate analysis described above assumes that the crack extension is coplanar with the initial crack. However, as observed in the experiments, the damage zone consists primarily of sub cracks oriented along the fibres of the unidirectional plies. A more realistic energy release rate analysis of the compact tension specimen should therefore be based on non-coplar crack extension. The problem then is to evaluate the energy release rate associated with the initiation of an infinite-simal kink AB as depicted in Fig.4. Let $G^{(\alpha)}$ be the energy release rate for the initiation of the infinitesimal kink AB at an angle α with respect to the plane of the initial crack, and let $G_B(c)$ be the energy release rate associated with hypothetical propagation of an existing Kink AB of length c along its own plane. Then we use the analysis by Ichikawa ad Tanaka [8,9] to calculate $G^{(\alpha)}$ as

$$G^{(\alpha)} = \lim_{c \to o} G_B(c) = \lim_{c \to o} [G_{IB}(c) + G_{IIB}(c)]$$

It is gratifying to note that we can use the finite element technique described in a previous paragraph to compute $G_{IB}(c)$ and $G_{IIB}(c)$ and hence $G^{(\alpha)}$.

The energy release rate analyses described above suppose that the crack is extending, without considering the conditions necessary to start and continue the extension. The purpose of a good fracture criterion is to represent the onset of crack growth in terms of basic material properties, whose predictions are in agreement with experimental data. The basic properties of a unidirectional composite material, which control interlaminar fracture behaviour are obviously the mode I and mode II components of interlaminar fracture touchness denoted by G_{IC} and G_{IIC} respectively. It is informative to note that simple test methods to determine G_{IC} and G_{IIC} have been recently proposed [10,5]. So, it is but natural that we look for a fracture criterion interms of G_{IC} and G_{IIC}. The specific criterion takes the form:

$$\frac{G_I}{G_{IC}} + \frac{G_{II}}{G_{IIC}} = 1 \qquad (1)$$

RESULTS AND DISCUSSION

The material properties of SCOTCHPLY 1002, used in the present study are: $E_L = 5.8 \times 10^6$ psi, $E_T = 1.2 \times 10^6$ psi, $G_{LT} = 0.6 \times 10^6$ psi, $\nu_{LT} = 0.26$, $G_{IC} = 1.23$ lb/in, $G_{IIC} = 8.2865$ lb/in.

The compact tension specimen(Fig.1) with a/w=0.5 was discretized using the TRIPLT finite element mesh also shown in Fig.1. The model comprises of 138 grid points, 220 elements and 825 degrees of freedom.

The accuracy of the calculated energy release rate $G = G_I + G_{II}$, by the chosen method of analysis depends, in addition to the finite element mesh, on the value of the incremental crack extension Δa; used in the computation. A value of $\Delta a/a = 0.025$, used in the present study, was chosen after solving several bench mark problems and comparing the results with known solutions. For example, figure 5 compares the analytical solution of Kanninen[11] for a double cantilever beam specimen (isotropic material) with the numerical results from the present analysis. The two solutions are in good agreement (within 2%) over a range of crack lengths.

The adequacy of the chosen finite element mesh to provide acceptable accuracy to the problem on hand was indirectly established by solving an otherwise identical homogeneous isotropic case. The mode I stress intensity factor denoted by K_I

was calculated from the computed value of G_I using the well known relationship between K_I and G_I [12]. The normalised stress intensity factor $K_I B\sqrt{W}/P = 9.3584$ obtained in the present study is in close agreement with the value of 9.5676 reported in Ref. [12].

Assuming coplanar crack extension, the computed values of the energy release rate G, are tabulated in Table 1 for $0^\circ \leq \alpha \leq 90^\circ$ and for P=1.0 lb. The magnitude of G_I is the highest for $\alpha=0^\circ$ and gradually decreases with α upto 70° and then shows a slight increase. G_{II} increases from zero at $\alpha=0^\circ$ to its maximum value at $\alpha=30^\circ$ and then gradually approaches zero again at $\alpha=90^\circ$. However, the magnitude of G_{II} is very small in comparison with G_I for all values of α. These results together with equation (1) are used to predict the fracture loads presented in Table 2. The results are also shown as solid circles in Fig.2. The increasing discrepancy between prediction and test data for α other than 0° is mainly attributed to the assumption of coplanar crack extension made in the energy release rate analysis.

As observed in experiments, the damage in the immediate vicinity of the crack tip consists of subcracks oriented along the fibres of the individual plies. The size of the damage zone increases with applied load upto a critical size at which point the specimen fails catastrophically. To model this failure mode in a simplified manner, a branch crack of length c=a/20, oriented at the angle α with respect to the plane of the initial crack was introduced. The configuration was discretised using the TRIPLT element mesh illustrated in Fig.6 consisting of 133 grid points and 216 elements resulting in 796 degrees of freedom. The computed values of G_{IB} (c) and G_{IIB} (c) for various values of the angle α coupled with the fracture criterion, equation (1) were used to predict the fracture loads and these are plotted as open squares in Fig.2. These are in closer agreement with test data than those based on the assumption of self similar crack growth. Several simplifying assumptions, made implicitly in the analysis appear to be responsible for the differences that still exist between the prediction and test data and these are briefly discussed in the following.

The accuracy of the computed values of $G^{(\alpha)}$ could not be judged, since no alternate solution was readily available for the particular problem. Further more, due to program limitations further mesh refinement to check the convergence of the solution was not attempted. Secondly, the finite element analysis assumes linear elastic stress strain response while the material exhibits non-linear behaviour especially at failure. Finally, the present analysis does not account for the growth of subcritical damage zones at the crack tip on the calculated energy release rate. It is hoped that a refined analysis taking into account the above factors will be able to further reduce the discrepancy between prediction and test data.

CONCLUSIONS

Based on the present study, the following conclusions can be drawn.

1. Interlaminar fracture in unidirectional composites under monotonically increasing load can be accurately predicted using linear elastic fracture mechanics.

2. The energy release rate provides a more useful parameter in the phenomenological study of interlaminar fracture in composites.

3. The finite element technique based on a high precision triangular finite element model and computation of crack closure integral is useful to calculate the energy release rate associated with coplanar as well a non-coplanar crack extension.

4. The computed energy release rate alongwith the mixed mode fracture criterion appears to predict, satisfactorily, the interlaminar fracture behaviour of unidirectional composites.

5. A significant amount of work remains to be done to generalise this approach for the prediction of the onset and growth of transverse cracking and delamination in laminated composite panels subjected to static and cyclic loads. In particular, the versatility and computational efficiency of the finite element technique used in the present study can be significantly improved by using the substructuring approach successfully used in Ref [13].

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Table 1. Energy Release Rate as a function of α: Standard Compact Tension Specimen with a/W=0.5, B/W=0.1, and P=1.0lb; Material Scotch ply 1002.

α	$G_{I} \times 10^{5}$	$G_{II} \times 10^{5}$	G_{II}/G_{I}
0	65.23023	0.0	0.0
10	63.968487	0.935555	0.0146252
20	61.029372	2.6553035	0.0435086
30	56.703346	3.6901673	0.0650785
40	52.558165	3.3826516	0.0643602
45	50.652989	2.9042318	0.0573358
50	48.971645	2.3586797	0.0481642
60	47.008395	1.373271	0.0292133
70	46.815144	0.665647	0.0142186
80	47.778318	0.860787	0.0180163
90	48.322108	0.0	0.0

Table 2: Comparison of predicted fracture loads with test data: Standard compact tension specimen with a/W=0.5, B/W=0.1; Material is scotch ply 1002.

α	Fracture load P_C lb-f Experiment	Prediction	Difference%
0	40.95	40.95	0.0
30	51.075	43.921179	14.0
45	58.05	46.470313	20.0
60	72.00	48.238159	33.0
90	110.025	47.577936	56.76

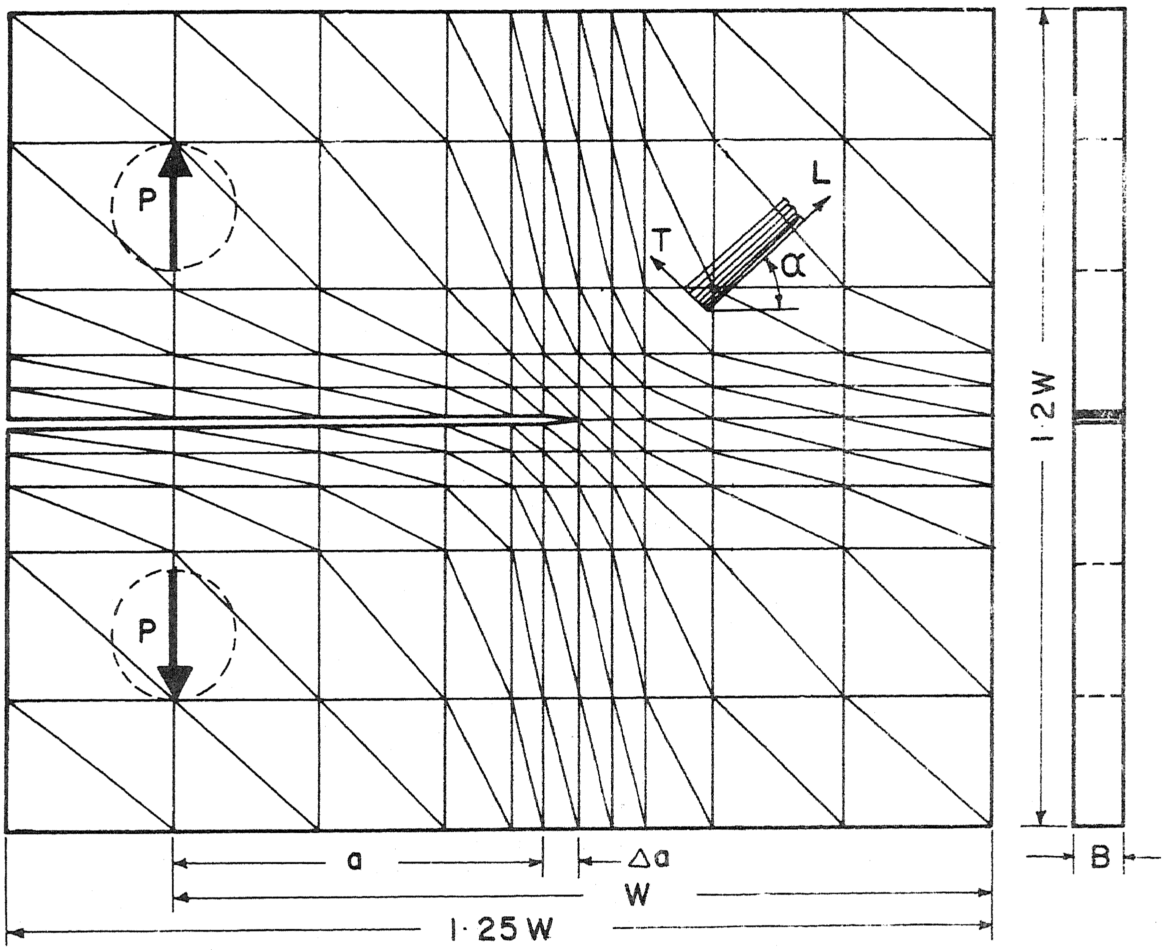


Fig.1 Standard Compact Tension Specimen and its TRIPLT Finite Element Model a/w =o.5, B/W=0.1.

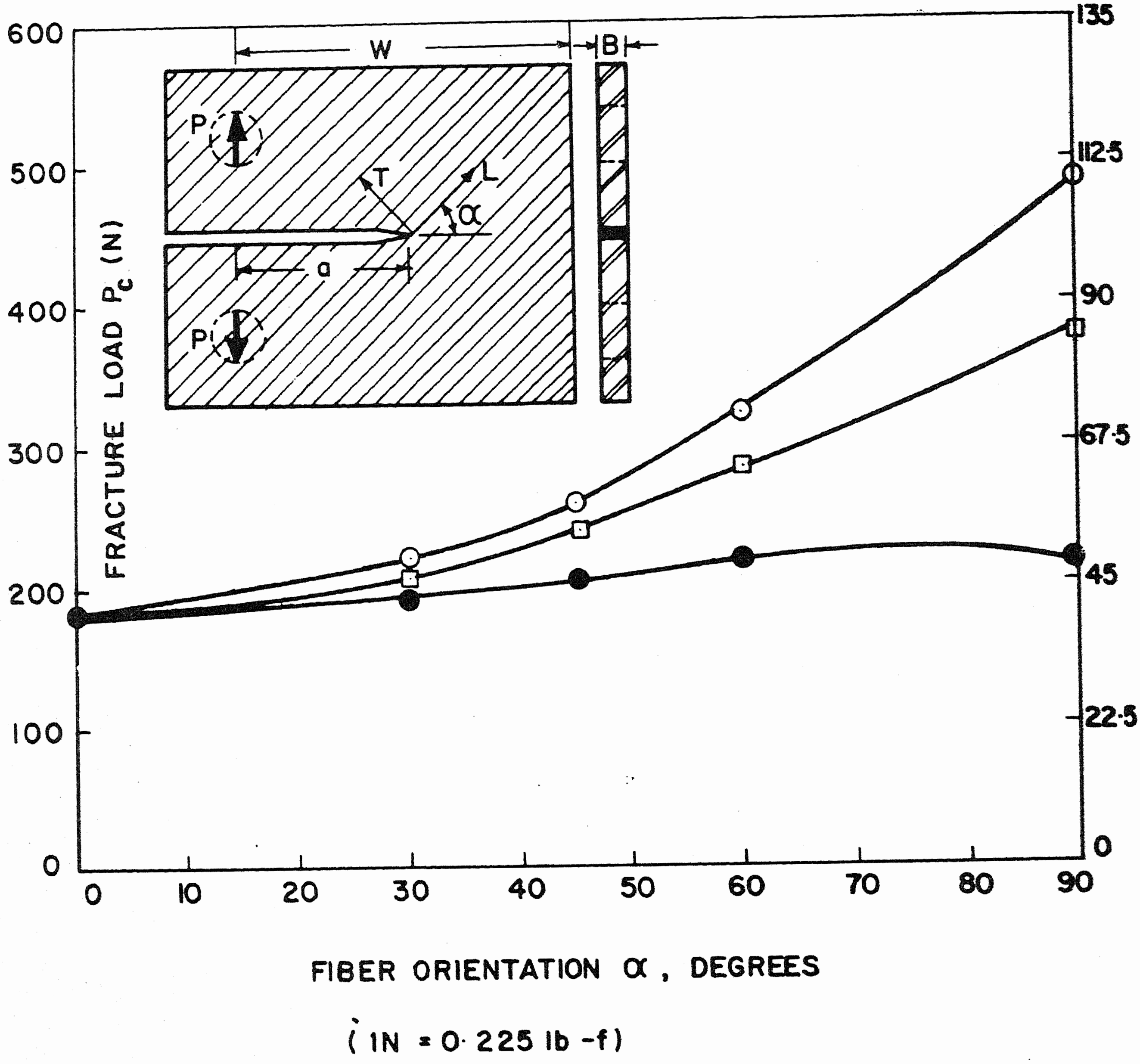
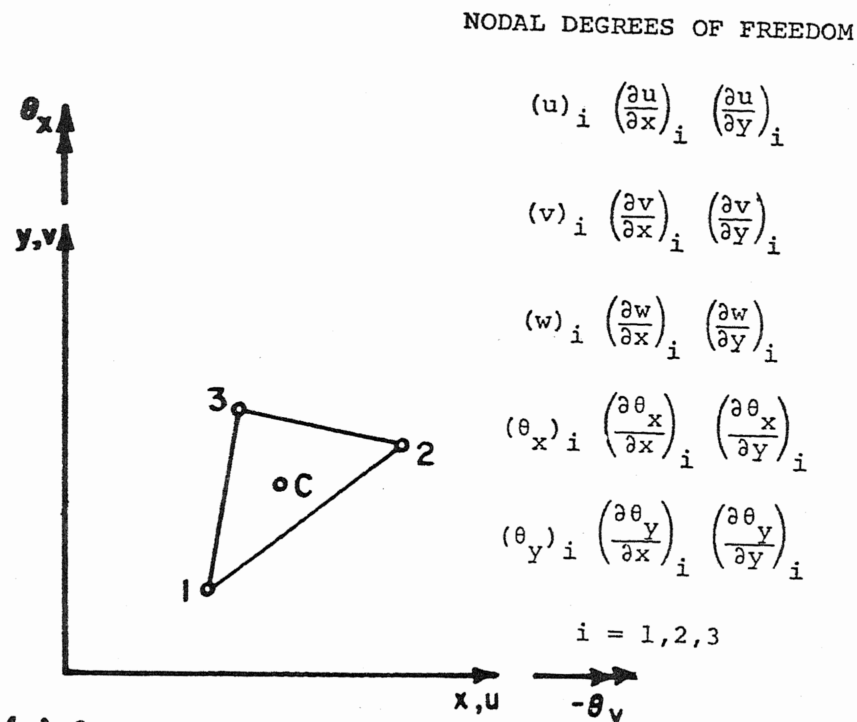
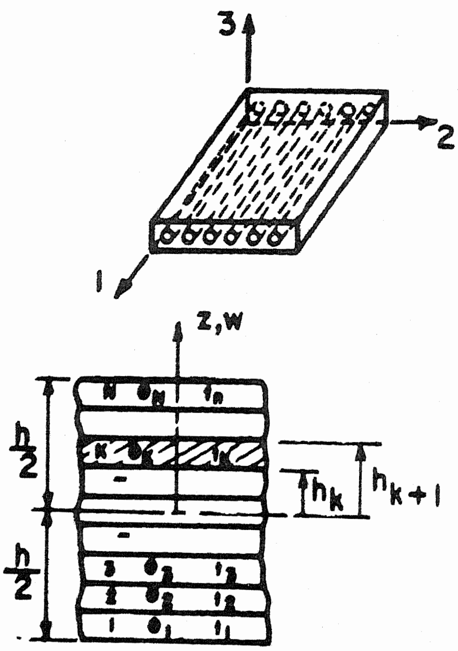


Fig.2 Variation of Fracture Load with Fibre Orientation.



(a) Geometry, coordinate system positive displacements and rotations, and nodal degrees of freedom.



(b) Composite laminate nomenclature.

Fig.3 Shear Flexible Triangular Laminated Composite Plate Finite Element - TRIPLT.

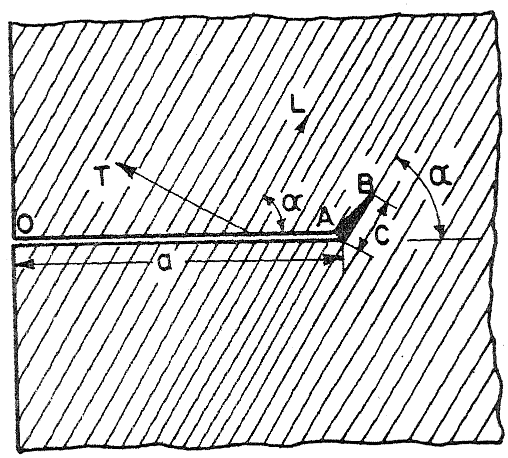


Fig.4 Non-coplanar crack Extension in the compact tension specimen

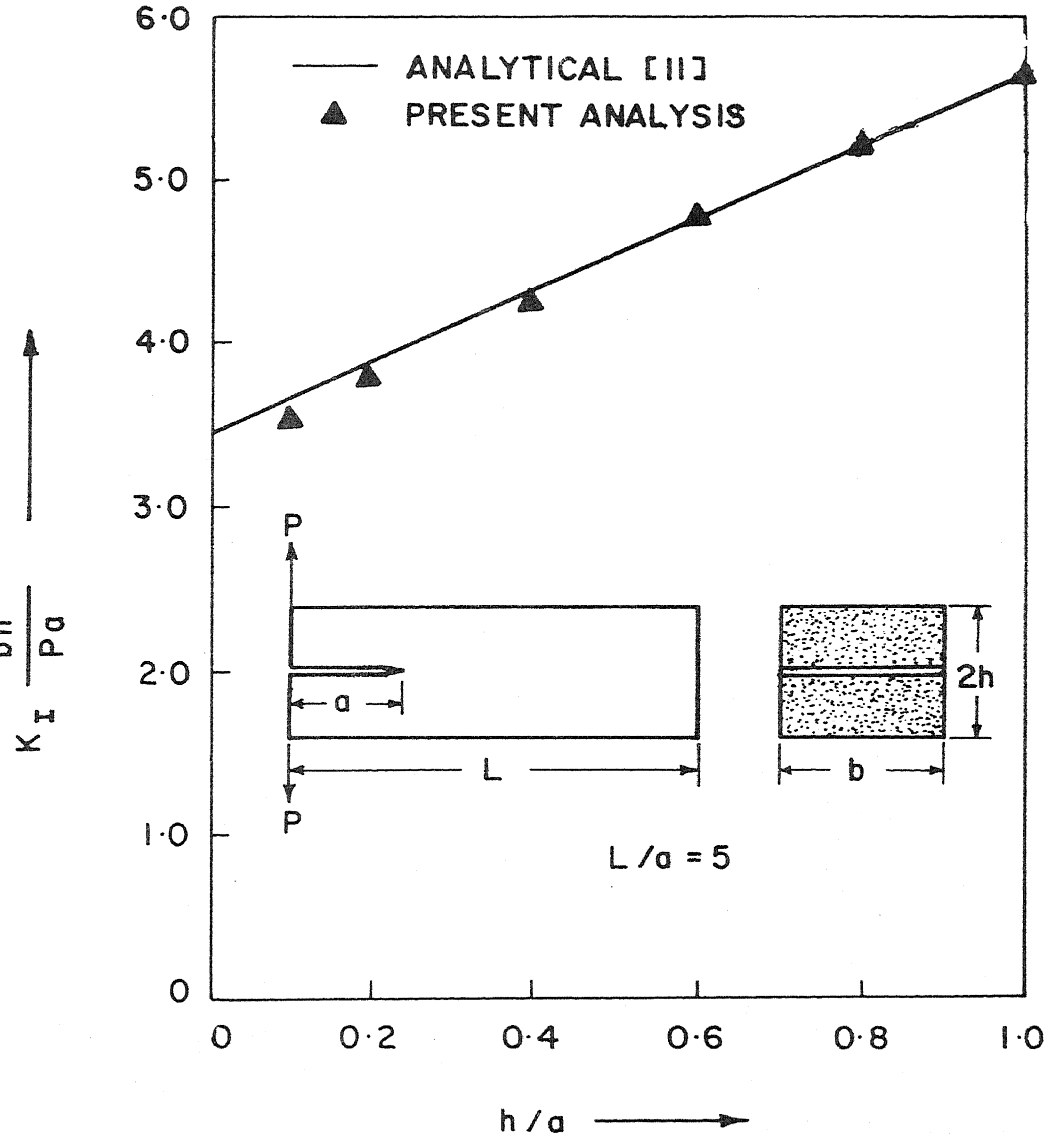


Fig.5 Comparison of Numerical Results with Analytical Solutions for a Double Cantilever Beam Test Specimen.

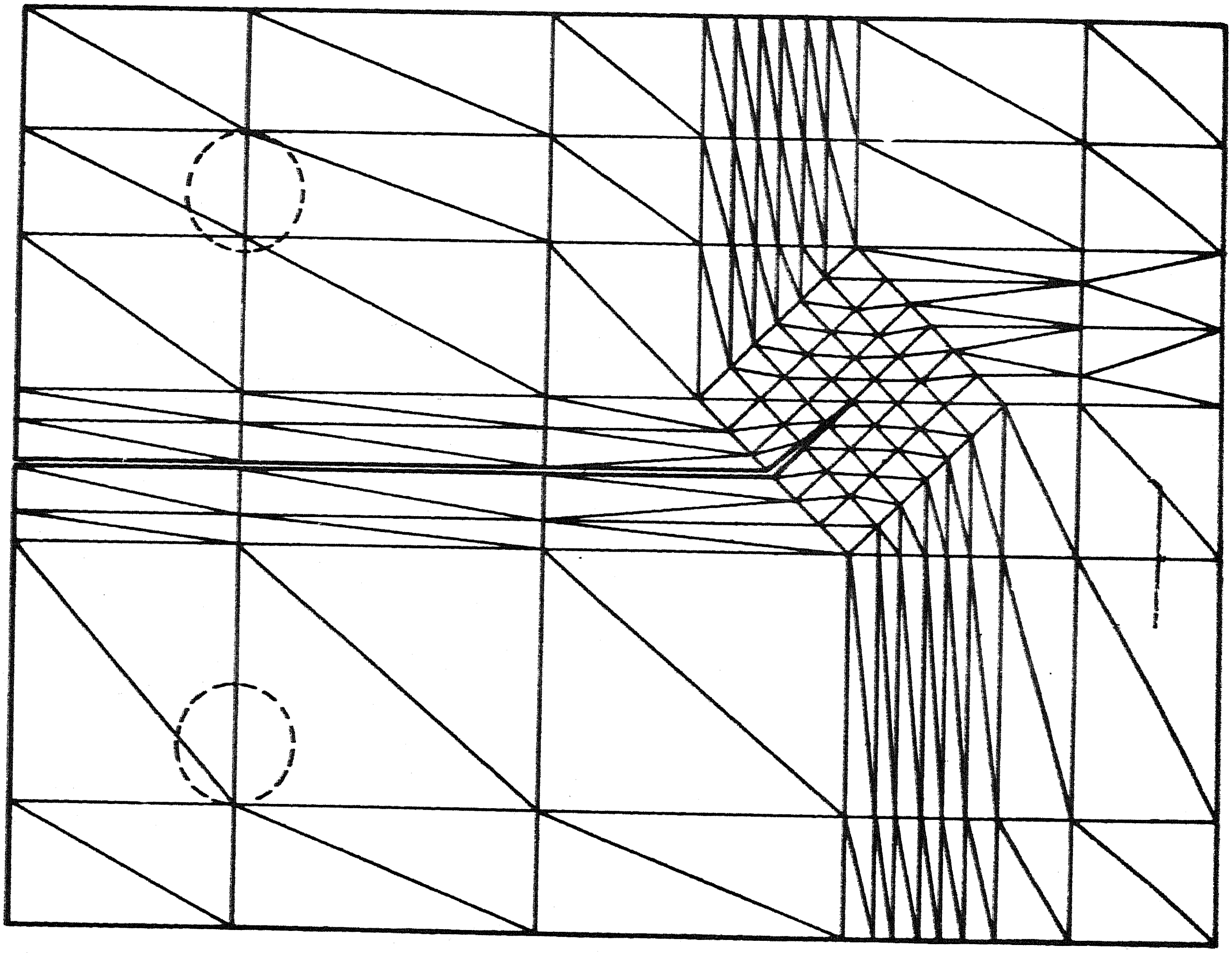


Fig.6 Finite Element Model of the standard compact tension specimen with a branch crack.